Final Report
In Situ Measurements of Coherent Structures and Turbulence
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LONG-TERM GOALS

The long-term objective of our research is to quantify the structure of turbulence in fluvial and estuarine environments, in order to develop remote-sensing tools for environmental assessment as well as to improve numerical simulations.

OBJECTIVES

The objectives of this program were:

- to quantify the turbulence length scale and turbulent dynamics in an estuary under varying stratification conditions and geometries, including relatively uniform boundary-layer flows and highly disrupted wake flow conditions;
- to quantify the key properties of observed coherent structures, including horizontal and vertical scales, intensity of vertical motions;
- to provide a field-scale test of turbulence closure models and large-eddy simulations via direct measures of turbulent kinetic energy, length scale and turbulent dissipation rate combined with accurate measures of the Reynolds-averaged quantities.

APPROACH

The Mobile Array for Sensing Turbulence (MAST) is a 10-m long aluminum structure with 6 sets of instruments for measuring the turbulent quantities and Reynolds-averaged velocity and density at multiple depths. The instrument is deployed off the side of a research vessel, either in underway mode or at anchor. The depths of the sensors are varied by the tilt of the mast, with the sensor spacing 1-1.5 m in the vertical. Turbulence quantities are measured with co-located Seabird SBE-7 micro-conductivity sensors and Sontek ADVs. The stratification is measured with RBR T-S sensors. The spatial resolution of turbulence measurements is 5-10 cm for velocity (limited by the 25 Hz sampling

rate of the ADVs and flows past the sensors of 50-100 cm/s), and less than 1 cm for conductivity (effective sampling rate 200 Hz).

Turbulence data from the MAST were evaluated using the proposed spectrum of Kaimal et al. (1972). Evaluating the data in this framework provided a theoretical methodology for separating turbulence from non-turbulent wave motion. This resulted in high quality estimates of the turbulent kinetic energy (k), turbulent dissipation (ε), integral turbulent length scale (L_T), and the turbulent fluxes of buoyancy ($B = g\rho^{-1}<\rho'w'>$.) and momentum ($<u'w'>$). In addition, the MAST provides high quality measurements of the mean flow with continuous temporal resolution at 6 vertical locations. Data from the MAST have been analyzed from three field sites including the Snohomish River (Summer 2006), the Hudson River (Fall 2006) and the Merrimack River (Spring 2007). Analysis has focused on synthesizing the results from these experiments to provide a more broadly applicable characterization of estuarine turbulence and to provide a high quality data set with which to test commonly used turbulence closure schemes.

RESULTS

In synthesizing the results from the three field experiments, one of the striking results is the frequency with which disequilibrium turbulence is observed (i.e. $P - B \neq \varepsilon$). While this was expected in the Snohomish River where much of the data was collected in the turbulent wake of a partially submerged jetty, significant spatial and temporal heterogeneity also was observed in the other systems. Figure 1 shows a histogram of the ratio of the shear production (P) to dissipation for all of the experiments. While the peak of the histogram is consistent with the expected first order balance of the turbulent kinetic energy equation, a significant fraction of the data deviated significantly from this balance.

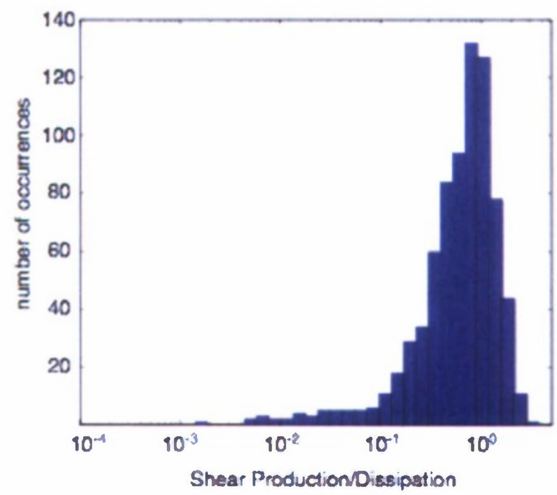

Figure 1. Histogram of the ratio of shear production to dissipation for all 3 field experiments.

In most Reynolds-averaged numerical models, the turbulent fluxes are parameterized in terms of an eddy coefficient that acts on the mean vertical gradient. Many two-equation turbulence models parameterized the eddy viscosity (ν_t) and diffusivity (ν'_t) as:

$$\nu_t = -\frac{<u'w'>}{\partial U/\partial z} = c_\mu \frac{k^2}{\varepsilon} \quad ; \quad \nu_t' = \frac{B}{N^2} = c_\mu' \frac{k^2}{\varepsilon} \qquad (1)$$

where c_μ and c'_μ are referred to as the "stability functions". The stability functions are non-linear functions, which depend on the non-dimensional shear ($\alpha_M = [du/dz]^2 k^2 \varepsilon^{-2}$) and non-dimensional stratification ($\alpha_N = N^2 k^2 \varepsilon^{-2}$). It is through the stability functions that most two-equation turbulence models account for the impact of stratification and disequilibrium turbulence on the turbulent fluxes. The MAST measurements provide estimates of all the quantities in (1), allowing us to rigorously examine the performance of several commonly used turbulence models using field data and evaluate the importance of disequilibrium conditions on parameterizing turbulent fluxes.

Figure 2 shows the comparison between the between the "observed" eddy viscosity and that calculated using several proposed formulations including a simple mixing length model that assumes a constant stability function, as well as the proposed stability functions of Kantha and Clayson (1994) and Canuto et al. (2000). While there is general agreement utilizing this approach, the comparison is improved in

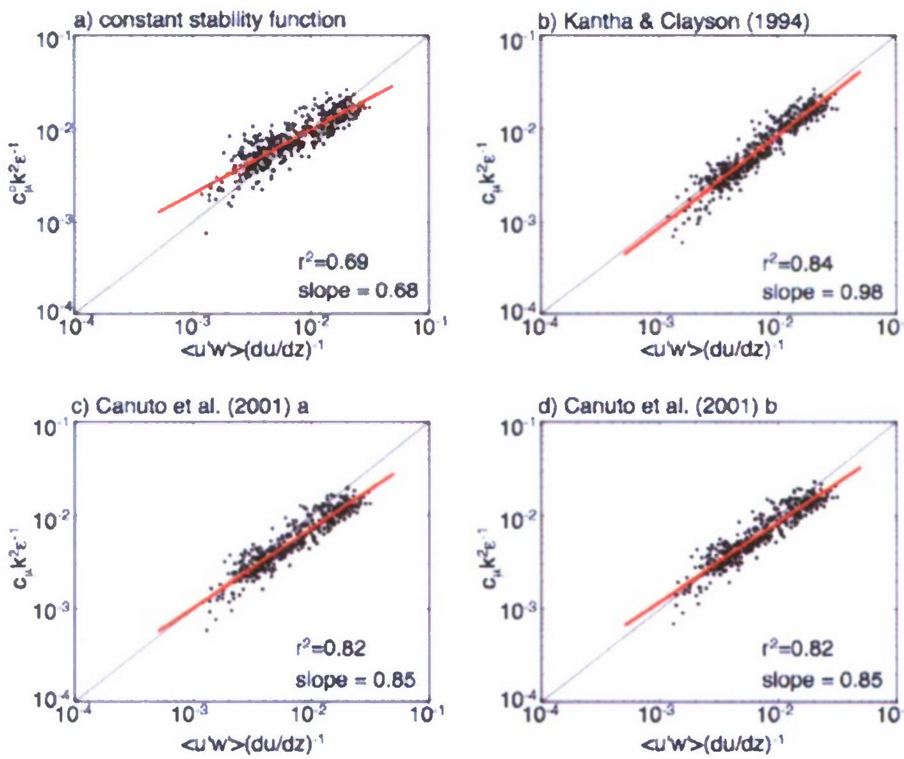

Figure 2. Comparison of the "observed" eddy viscosity to eddy viscosity calculated based on a) a simple mixing length model; b) stability functions of Kantha and Clayson (1994); c) stability functions of Canuto et al. (2000) A; d) stability functions of Canuto et al. (2000) B.

all cases where the impact of disequilibrium turbulence and stratification are accounted for via the stability functions. To examine more specifically how the various stability functions perform, we compare the predicted value of the c_μ, with the "observed" value, which is back calculated from equation (1) using the observed quantities. This comparison is shown in Figure 3 for the 3 stability functions considered. Consistent with results shown in Figure 2, the formulation proposed by Kantha and Clayson (1994) agrees best with our observations. This closure performs the best for this data set because it more accurately accounts for the impact of disequilibrium turbulence. This is demonstrated in figure 3d-e, where the "observed" value of the stability function is contoured as a function of α_M and α_N over top of contours for each of the proposed stability function. On each contour plot, the thick

white line corresponds to the equilibrium condition. Moving off the white line represents deviations in the stability functions due to disequilibrium conditions. The stability function of Kantha and Clayson (1994) demonstrates a greater sensitivity to disequilibrium conditions as seen in the spacing of the contours in figure 3d. The sensitivity of to disequilibrium is weaker in both of the Canuto formulations, which leads to the greater curvature seen in figures 3b-c.

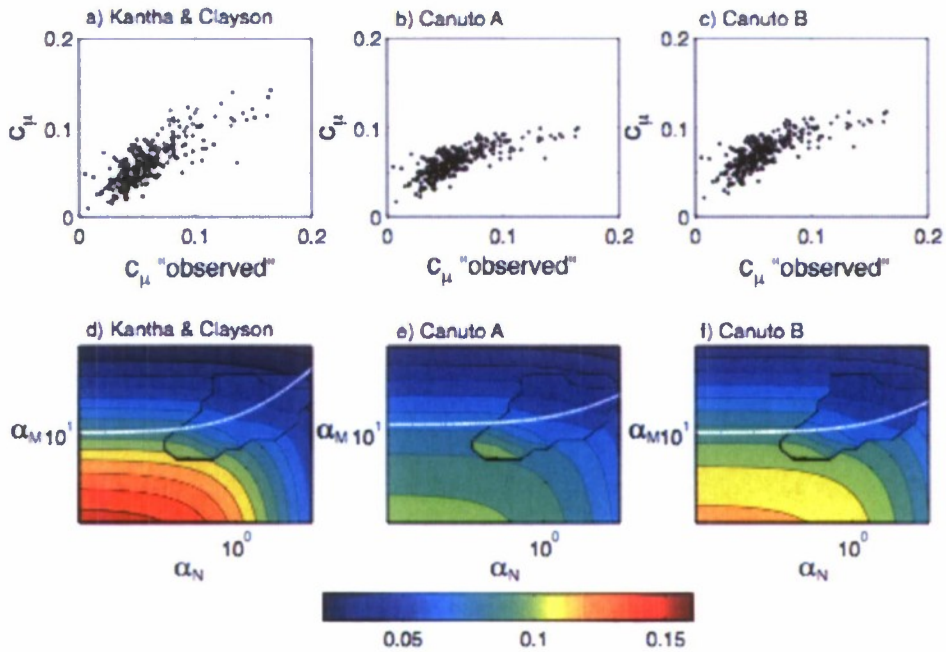

Figure 3. Comparison of the "observed" momentum stability function to the formulations proposed by Kantha and Clayson (1994) and the two forms proposed by Canuto et al. (2000) a-c . Contours of the stability functions as a function of non-dimensional shear and stratification compared with the "observations" d-e. Solid white line corresponds to equilibrium conditions.

Results from the MAST have demonstrated that turbulence in estuaries is highly heterogenous in both time and space, often deviating significantly from the commonly assumed production-dissipation balance. Accounting for this heterogeniety is particularly important in environments in which the spatial and temporal scales of forcing are not widely separated from the spatial and temporal evolution scale of the turbulence. Estuaries and rivers certainly fall in this category, and mixing associated with internal waves may also exhibit non-equilibrium behavior. The Kantha and Clayson closure appears to best parameterize the turbulence quantities in these non-equilibrium situations, but whether or not that translates directly into more accurate simulations remains to be tested.

IMPACT/APPLICATIONS

This study provides a quantitative test of turbulence closures that suggests that the Kantha and Clayson approach should be applied in simulations with heterogeneous and transient Reynolds-averaged flows. Additional direct comparisons between turbulence measurements and prognostic model results are requred to provide a definitive recommendation for application of turbulence closure.

PUBLICATIONS

Geyer, W.R., M.E. Scully and D.A. Ralston, 2008. Quantifying vertical mixing in estuaries. Environmental Fluid Mechanics, **8**, 495-509.

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